cleanout. In locations such as underpasses, and sag vertical curves in depressed sections, it is good engineering practice to place flanking inlets on each side of the inlet at the low point in the sag. For a more thorough discussion of this subject, refer to Hydraulic Engineering Circular No. 12 (March, 1984).

Pipe Sizing

Determination of required pipe sizes for storm drains is based on Manning's equation:

$$Q = \left[\frac{1.486}{n} \times R^{2/3} \times A\right] \times S^{1/2}$$

where Q = design discharge in cfs;
n = Manning's coefficient of roughness;
R = hydraulic radius, in feet;
A = pipe end area, in square feet; and
S = pipe slope, in feet per foot.

An important variable in the equation is "n," Manning's roughness coefficient. For reinforced concrete pipe, the coefficient is constant for all pipe sizes. For annular corrugated metal pipe, the coefficient is constant for all sizes -- but will vary if part or all of the inside of the pipe is paved. In the case of helical corrugated metal pipe, the coefficient varies with the size of pipe, and also with regard to the extent of paving. Figure 6-17 shows the appropriate values of "n" for the various types and sizes of pipe.

The value shown within the brackets in the Manning equation can be referred to as the "conveyance factor." The value for "Q" can be found by multiplying this factor by $S^{1/2}$. Figure 6-18 shows the conveyance factors for round corrugated pipe for various values of "n." Figure 6-19 shows the conveyance factors for corrugated arch pipe for various values of "n." And Figure 6-20 shows values for $S^{1/2}$ for various rates of slope.

Gradients

Storm drain grades should be established to assure a minimum velocity of at least 2 feet per second. The purpose is to prevent buildup of sediment.

Storm drain line gradients should be generally similar to the roadway grade. The same size of pipe will run until the cumulative discharge attains the pipe capacity. When an abrupt reduction in gradient is encountered, an increase of more than one pipe size larger may be required.

When increasing the size of pipe, two alternatives are available for design at the junction:

- Align the pipe inverts (inside bottom of pipe) with a continuous flow line; or

- Align the inside top of the pipe (soffit) with an abrupt drop in the flow line.

Each alternative has advantages and disadvantages. The hydraulic characteristics generally are better when the tops of the pipes are aligned. Also, this approach is better where there is a problem with minimum allowable cover over the pipes. On the other hand, there may be situations in relatively flat terrain where it is necessary to conserve the elevation of the flow line. Under these conditions it may be better to avoid the abrupt drops by aligning the pipe inverts at the junction.

Hydraulic Gradient

A hydraulic gradient is the line of elevations to which the water would rise in successive piezometer tubes along a storm drain run. Differences in elevations for the water surfaces in the successive tubes represent the energy loss for that length of storm drain.

The storm drain run will not be under pressure if it is placed on a calculated friction slope corresponding to a certain quantity of water, cross-section, and roughness factor -- and the surface of flow (hydraulic gradient) will be parallel to and below the top of the pipe. This is the desirable condition.

There may be reason to place the storm drain run on a slope less than the friction slope. In that case, the hydraulic gradient would be steeper than the slope of the storm drain run. Depending on the elevation of the hydraulic gradient at the downstream end of the run, it is possible to have the hydraulic gradient rise above the top of the pipe, creating pressure on the storm drain system until the hydraulic gradient at some point upstream is once again at or below the top of the pipe.

The hydraulic gradient is determined starting at the downstream end of the proposed system. Where the system is connected to all existing drainage systems, the hydraulic gradient at the point of junction shall be determined from the hydraulic gradient computations for the existing drain. If the proposed system is to discharge into a stream, flow conditions of the stream shall be investigated. Where the tailwater elevation is higher than the proposed crown elevation, the hydraulic gradient will begin at this tailwater elevation. If free outfall conditions exist, the gradient will begin at the crown of the proposed drain.

Next, the friction loss in the pipe to the next structure is added to the gradient. Then the head loss in the structure is added. The hydraulic gradient to the upstream end is thus determined by adding a series of friction losses in pipes and head losses in structures. To avoid creating a pressurized system (major cause of blow ups and joint failures), the hydraulic gradient should not exceed the pipe crown.

Head loss in pipes due to friction can be calculated using Manning's formula, by solving for S_f.

$$S_f = \left(\frac{Qn}{1.486\ AR^{2/3}} \right)^2$$

where Q = discharge (cfs);

n = roughness coefficient;

A = cross sectional area (sq. ft.); and

R = hydraulic radius (D/4 for circular pipes) (ft.).

The head loss is calculated from the formula:

$$H_f = S_f \times L$$

where L = length of pipe (ft.)

To compute head losses in structures, Figures 6-21 and 6-22 should be used. These curves were prepared for the determination of head loss in cut-ins, wye branches, preformed concrete pipe fittings, manholes, brick bends, and Type I junction chambers.

There are four curves, designated as "A," "B," "C," and "D" losses. The "A" curve gives losses due to entrance and exit. The "B" curve depicts velocity head. When there is a change in velocity, the difference in the velocity heads (V_{H-2} - V_{H-1}) is the head loss. If the upstream velocity is greater, this difference will be negative and the apparent gain may be used to offset other losses in the structure. The "C" curve shows losses in a manhole due to change in direction, loss in wye branch, and loss in brick bend. The "D" curve depicts losses due to entrance of secondary flows into a structure.

Computation of the hydraulic grade line will not be necessary where the following conditions are satisfied:

1. The slope and the pipe sizes are chosen so that the slope is equal to or greater than the friction slope;

2. The top surfaces of successive pipes are aligned at changes in size (rather than flow lines being aligned); and

3. The surface of the tailwater at the point of discharge does not rise above the top of the outlet.

The pipe will not operate under pressure in these cases, and the slope of the water surface under capacity discharge will approximately parallel the slope of the pipe invert. Small head losses at inlets, manholes, etc., may be disregarded if these structures are properly designed.

However, in cases where different sized pipe inverts are placed on the same grade, causing the smaller pipe to discharge against head, or when it is desired to check the storm drain system against larger-than-design floods, it will be necessary to compute the hydraulic grade of the entire storm system. Begin with the tailwater elevation at the storm drain outfall and progress upward the length of the storm drain. For every run, compute the friction loss and plot the elevation of the total head at each manhole and inlet.

If the hydraulic grade line rises above the top of any manhole or above an inlet entrance, the storm drain system is unsatisfactory because blowouts will occur through manholes and inlets. Pipe sizes or gradients must be increased as necessary to eliminate such blowouts.

A hydraulic gradient must have an original base elevation above the outlet tailwater elevation. Any backwater effects due to a significant tailwater elevation must be considered carefully.

Typical details for drop inlets, manholes and grates are shown in the Department's Standard Sheets.

Conflict with Underground Utilities

Construction of new storm drains raises the possibility of conflicts with existing underground utilities. Designers should check thoroughly for underground utilities before commencing design. Often it is possible to avoid conflicts by making minor adjustments in the line or grade of the storm drain. All recognized conflicts should be clearly identified and brought to the attention of the Utilities Section.

Hydraulic Analysis of Inlet Grates

The flow intercepted by an inlet grate consists of two parts: (1) frontal flow, the portion of the flow which passes over the upstream edge of the grate, and (2) side flow, which passes over the edge of the grate parallel to and away from the curb. The percent of frontal flow intercepted depends on the bar configuration, grate length, and flow velocity. All of the frontal flow will normally be intercepted on mild slopes. On steep slopes, the water may splash over the grate and not be intercepted. The amount of side flow intercepted decreases with increasing velocity, and increases with increasing grate length.

The hydraulic efficiency (E) of a grate is defined as the ratio of the total flow intercepted (Q_i) to the total gutter flow (Q_T).

$$E = Q_i/Q_T$$

For grates on a continuous slope, the quantity of flow intercepted increases as the flow rate increases. Thus, a percentage of the gutter flow may be allowed to flow around the inlet, to be picked up by downstream inlets or at the sump. The spacing of inlets on continuous grades is therefore determined by the allowable width of water on the pavement and the efficiency of the inlets.

If it is assumed that there is no side flow interception (only the flow passing over the front edge enters the grate) then the ratio of approach frontal flow (Q_F) to total gutter flow (Q_T) is given by the equation:

$$\frac{Q_F}{Q_T} = 1 - \left[1 - \frac{W}{T}\right]^{8/3}$$

where W = width of grate (ft.); and
T = spread on pavement (ft.).

To account for side flow, an effective width, W_E, is substituted for W in the above equation. The effective width is equal to the actual width plus the extra width, ΔW, that would be necessary for the inlet to have the same efficiency without side flow interception. ΔW is a function of longitudinal slope, cross slope, grate size, and bar configuration. Values for ΔW for eight grate configurations can be obtained from from charts in Chapter 5 of the FHWA publication "Design of Urban Highway Drainage -- The State of the Art" (August 1979).

The equation for calculating the grate inlet efficiency is then:

$$E_o = 1 - \left[1 - \frac{W_E}{T}\right]^{8/3}$$

This relationship applies only for no-splash conditions. If splashing will occur, this equation must be multiplied by a reduction factor, R. (See referenced FHWA publication.) The hydraulic efficiency is related to the inlet efficiency by the equation:

$$E = RE_o$$

Grate inlets should be designed longer than necessary for 100% frontal flow interception to allow for debris accumulation and clogging. It is recommended that grates be designed with a factor of safety of at least 1.5. The factor of safety is defined for a particular effective grate length, L', as the ratio of the frontal velocity at which 100% of the frontal flow is intercepted to the actual frontal velocity.

For a more thorough discussion of this subject, refer to Hydraulic Engineering Circular No. 12 (March, 1984).

Summary of Design Steps

The steps for designing storm-drainage system are as follows.

1. Prepare a drainage-area map using:

   a. U.S.G.S. maps and contour maps;

b. existing drainage structures and their elevations (an accurate field investigation must be performed);

c. field data -- outlet and scour conditions, ground surface type and proposed land use of drainage area -- and

d. soil type and water table elevations, which are needed for subsurface drainage.

2. Divide drainage area into subareas tributary to the proposed storm inlets, showing drainage limits, streets, impervious areas and direction of flow.

3. Compute acreage of each subarea.

4. Determine the appropriate runoff coefficient (C) for each subarea.

5. Determine the appropriate storm frequency to be used in design (Figures 6-13 through 6-15).

6. Determine the initial time of concentration (Tc) from Figure 6-12 (Tc_{min} = 5 Min.), and the rainfall intensity for this Tc from the appropriate rainfall intensity-frequency curve.

7. Using existing survey and field data, lay out a tentative drainage system, giving lengths and slopes of pipes, type and number of catch basins or manholes, and the direction of flow. Begin the profile at the point farthest downstream, which can be an outfall into a natural or artificial channel, or into an existing drain. Pipe slopes should conform to the surface slope wherever possible.

8. Complete the storm drainage design table using the proposed lengths and slopes to determine the proper pipe sizes necessary to accommodate the estimated runoff. (Detailed instructions for the completion of the table are given in subsequent sections.)

9. Plot profile of the proposed system using the pipe sizes calculated in Step 8. At all drainage structures, indicate the necessary change in invert elevations. Where there is no change in pipe size through a structure, a drop of 0.2 feet should be used if fall is available. Where the size increases downstream through a structure, the inside top of the pipes should be aligned, providing an invert drop at the outlet equal to the difference in the two pipe diameters.

10. Determine the hydraulic gradient for the system by calculating the friction head for each reach and the head loss in each structure. To avoid blowouts, it is desirable that the gradient not come within 1.5 feet of the surface. The system must be modified to eliminate this condition if it exists. This could be accomplished by reducing head losses, increasing the depth of the structure, or both, depending upon cost.

11. Analyze the curb, gutter and inlet hydraulics for the proposed types, to determine their capacities, flow depth, and spread. Also compute the probable depths at structure inlets. The ponding and spreading of flow must not exceed the limits specified. The nomograph, Figure 6-16, can be used to determine flow depths and spread in gutters. For grate inlets in sumps, Figure 6-23 is useful, and refer to HEC No. 12 (March, 1984).

12. Using sound engineering judgment, and taking into consideration the pipe sizes needed (Step 8), the hydraulic gradient (Step 10) and the actual quantity of water that gets into the system (Step 11), complete the design for the drainage system.

Use of Storm Drainage Design Sheet

The Storm Drainage Design Sheet (see Figure 6-3) is the basic documentation of the design process. The columns should be completed as follows.

1. Location: Manholes and inlets are to be numbered. The corresponding numbers for each reach are then entered in the first columns, starting at the upstream end of the system.

2. Increment area: Enter the acreage of the tributary areas for each reach.

3. Initial time of concentration: Determine from the overland flow time chart (Figure 6-12) plus the time in the facility.

4. Rainfall intensity: Determine from the appropriate intensity-frequency curve.

5. Runoff coefficient: Some tributary areas may contain portions that have different permeabilities (e.g., part grass, part pavement.). An average runoff coefficient must be calculated. This is done by calculating the area of each portion of the sub-area having a different coefficient. The average coefficient is then the sum of the products of these areas and their respective coefficients, divided by the total area.

6. Discharge: Beginning at the upstream end of the system, compute the discharge to be carried by each successive length of pipe. Note that at each point downstream where a new flow is introduced, a new time of concentration must be determined.

7. Pipe size: Select the appropriate slope and use Figures 6-18, 6-19 and 6-20 to determine the pipe size.

8. Just full capacity and mean velocity: Determine the capacity of the pipe when it is flowing full from the figures referenced in Step 7. Divide this capacity by the cross-sectional area of the pipe to obtain the mean velocity.

9. Flow time: First compute the actual velocity of the flow in a pipe from the ratio of the actual discharge to the just full capacity (Q_{ACT}/Q_{JF}) and the mean velocity using Figure 6-24 or 6-25. Divide